# Infiltration and erosion in soils treated with dry PAM, of two molecular weights, and phosphogypsum

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**Abstract.** Soil surface application of dissolved linear polyacrylamide (PAM) of high molecular weight (MW) can mitigate seal formation, runoff, and erosion, especially when added with a source of electrolytes (e.g. gypsum). Practical difficulties associated with PAM solution application prohibited commercial use of PAM in dryland farming. An alternative practice of spreading dry granular PAM with high MW on the soil surface has been ineffective in reducing runoff while effectively reducing erosion. The objective of this study was to investigate the mechanism by which granular PAM (20 kg/ha), with moderate ( $2 \times 10^5 \text{ Da}$ ) or high ( $1.2 \times 10^7 \text{ Da}$ ) MW, mixed with phosphogypsum (PG) (4 Mg/ha) affects infiltration rate, runoff, and erosion. Five smectitic soils, treated with PAM and PG, were exposed to simulated rainfall of deionised water in the laboratory. Both dry PAMs, mixed with PG, increased final infiltration rate (3-5 times) and reduced erosion (2-4 times) relative to the control (no amendments). Whereas the polymers' effects on the infiltration rate and runoff relative to each other were inconsistent, PAM with moderate MW was consistently more effective in reducing soil loss than PAM with high MW. For example, in the sandy clay soil, soil losses were reduced from  $840 \text{ g/m}^2$ , in the control, to  $570 \text{ and } 370 \text{ g/m}^2$  for the high and moderate MW PAM treatment, respectively. This greater capacity to control soil erosion was ascribed to the lower viscosity of the soil surface solution following dissolution of dry PAM granules in the case of moderate MW PAM, leading to more uniform, effective treatment of soil aggregates at the soil surface by the polymer.

**Additional keywords:** PAM molecular weight, dissolution rate, seal formation, runoff, viscosity.

## Introduction

Sustainable development and use of soil resources requires maintaining soil structure and reducing or eliminating sediment and pollutant discharge by runoff and erosion. Reduced rainwater infiltration rates (IR), which result from seals formed by a combination of aggregate disintegration under raindrop impact and dispersion of clay particles at the soil surface (Agassi et al. 1981), lead to runoff, erosion, and inefficient water use. Amendments such gypsum (or phosphogypsum, PG) and anionic polyacrylamide (PAM) have been used to prevent seal formation, runoff, and erosion from a range of soils exposed to rainstorms with various properties and/or cultivation histories (Shainberg et al. 1990; Agassi and Ben-Hur 1992; Fox and Bryan 1992; Levy and Agassi 1995; Flanagan et al. 1997a, 1997b; Yu et al. 2003; Ajwa and Trout 2006; Tang et al. 2006; Sojka et al. 2007). Use of PG is effective because, upon dissolution, it releases electrolytes into the rainwater, which reduce clay dispersion and thus reduce aggregate disintegration (Keren and Shainberg 1981). Water-soluble, linear PAMs are effective because they stabilise soil structure, prevent clay dispersion, and improve clay flocculation (Shainberg and Levy 1994; Ben-Hur and Keren 1997; Green *et al.* 2004; Sojka *et al.* 2007). However, the addition of dissolved PAM may have some negative aspects such as increasing water viscosity, which in turn could lead to a decrease in the IR and increased runoff, although possibly to a decrease in soil erosion (Ben-Hur and Keren 1997; Ajwa and Trout 2006; Sojka *et al.* 2007).

The molecular properties of PAM (molecular weight (MW) and molecular charge density) may interact in affecting the PAM's efficacy in flocculating soil clay, stabilising soil aggregates, diminishing seal formation, and resisting erosion (Green *et al.* 2000, 2004). Increasing the MW of linear PAM increases the length of the polymer chain. The longer the polymer molecules, the larger the number of points where it can be adsorbed to the mineral surfaces and, thus, the more effective the PAM molecules are as a flocculant (Malik and Letey 1991). Moreover, Heller and Keren (2002), who studied the rheological behaviour of Na-montmorillonite suspensions,

Abbreviations: IR, infiltration rate; MW, molecular weight; PAM, polyacrylamide; PG, phosphogypsum.

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reported that the higher the MW of PAM, the more effective its ability to stabilise flocs of clay in a free electrolyte clay suspension. Thus, it might be expected that PAM with high MW will be more effective in stabilising the soil surface and preventing seal formation.

Contrary to the studies on clay material, investigations of the response of soils to an application of dissolved PAM with various MWs yielded different results. Green et al. (2000, 2004), studying the effect of dissolved anionic PAMs with different MWs (6–18  $\times$  10<sup>6</sup> Da) on IR and aggregate stability, concluded that the different PAMs were equally effective in increasing the IR and aggregate stability of soils exposed to rain, but that there was little impact of PAM MW. Similarly, Mamedov et al. (2007), studying aggregate stability of 4 smectitic soils varying in clay content (loam to heavy clay) as affected by the MW of dissolved PAM, concluded that: (i) presence of PAM, irrespective of its MW, improved aggregate stability in comparison to that of non-treated aggregates; and (ii) there was no significant effect of PAM MW. Also, Levy and Agassi (1995), studying the effect of MW of PAM ( $2 \times 10^5$  and  $2 \times 10^7$  Da) dissolved in irrigation water on IR and erosion in 3 soils of different textures, found that both polymers had similar effects on reducing erosion from all three soils and that the effect of polymer MW on the IR was small and dependent on soil texture.

In order to mitigate soil surface seal formation and the resultant problems of runoff and erosion under rain conditions (e.g. for dryland farming), PAM has to be added to the soil surface before the rainy season either by spraying a PAM solution (400–1000 mg/L) onto the soil surface (Shainberg et al. 1990; Levy and Agassi 1995; Peterson et al. 2002a) or as a dry powder that is spread on the soil surface and subsequently dissolved by rain water (Peterson et al. 2002b; Yu et al. 2003; Tang et al. 2006; Sojka et al. 2007). Spreading dry PAM on the soil surface has the advantages of low shipping costs and longer shelf life, and it avoids the practical difficulties involved in dissolving the dry PAM in water and eliminates the need to handle and spray the viscous PAM solution (Barvenik 1994).

Studies in which surface application of PAM (irrespective of the method of application) was supplemented with gypsum (a source of electrolytes) resulted in significantly greater final IRs and less runoff and erosion compared with no amendment (control) or applications of each amendment alone (Shainberg et al. 1990; Levin et al. 1991; Peterson et al. 2002b; Yu et al. 2003; Tang et al. 2006). In the presence of electrolytes, e.g. in gypsum solution, the negative charge and the thickness of the diffuse double layer at the clay and polymer surfaces is suppressed, resulting in decreased repulsion forces and greater adsorption by soil particles of the anionic polymer (Letey 1994; Shainberg and Levy 1994). In addition, the dissolved PG increases the electrolyte concentration in the soil solution to values above the flocculation value of the soil clay (Oster et al. 1980). The latter has been reported to be effective in enhancing the cementing and stabilisation of aggregates at the soil surface by anionic polymers (Smith et al. 1990; Levy and Agassi 1995; Lentz and Sojka 1996; Orts et al. 1999). Moreover, it was reported that an application of dry PAM in combination with PG was very effective in

increasing infiltration and reducing erosion in smectitic soils having very high exchangeable sodium, i.e. highly dispersive soils (Tang *et al.* 2006).

Therefore, it can be concluded that the effectiveness of treating the soil with PAM (irrespective of the method of application) together with PG in controlling seal formation and runoff is related to both slowing of the physical disintegration of surface aggregates by the PAM and the prevention of chemical dispersion by the PG (Shainberg *et al.* 1990; Levin *et al.* 1991). It is further suggested that, in the case of adding PAM to the soil surface in the form of dry granules, the presence of electrolytes contributes also to the formation of a less viscous solution of the dissolved PAM, and thus to mitigation of viscosity-related reductions (see *Results and discussion*) in soil permeability (Yu *et al.* 2003).

The effect of PAM MW, applied in the form of dry granules and mixed with gypsum, on IR, runoff, and erosion has not been studied. The rate of dissolution of dry PAM granules in water does not seem to be affected by its molecular weight; however, the viscosity of a PAM solution increases substantially with an increase in PAM MW and concentration (Volk and Friedrich 1980). Soil hydraulic conductivity is inversely related to the viscosity of the fluid used. Malik and Letey (1992) reported that the hydraulic conductivity of both coarse and fine sand decreased substantially with the increase in the viscosity of the PAM solution tested. It is suggested, therefore, that the effectiveness of dry PAM in decreasing runoff and erosion may depend on the balance between (i) the positive impact of PAM as a flocculating agent, and (ii) the adverse impact of the viscosity of the soil solution containing dissolved PAM on soil permeability and soil erosion. Both effects are expected to increase with an increase in PAM MW. Understanding the interactions between these effects may lead to the development of more effective strategies for combating runoff and erosion from steep slopes exposed to high intensity rain. Thus, our objective in this study was to determine the effect of PAM MW, when added as dry granules combined with an application of PG, on IR, runoff, and erosion from 5 smectitic soils varying in texture.

#### Materials and methods

Soils

Samples of 5 calcareous, smectitic soils (Banin and Amiel 1970), representing the main arable soils in Israel, were collected from the cultivated layer (0–250 mm) for use in this study. The soils were: a loamy sand (Typic Haploxeralf) from the coastal plain; a loam (Calcic Haploxeralf) from Be'er Sheva Valley; a dark brown sandy clay (Chromic Haploxerert) from Hafetz Haim, the Pleshet Plains; and 2 dark brown clays (Typic Haploxererts) from Yagur (clay-Y), in the Zevulun Valley, and Eilon (clay-E) from the Western Galilee. Selected physical and chemical properties of the soils, determined by standard analytical methods (Page *et al.* 1982; Klute 1986), are presented in Table 1.

## Rain simulation studies

The experiments were performed with a drip-type rainfall simulator. The simulator consisted of a closed chamber 750

| S          | Soil        | Particl | e-size distr   | ibution | CEC                     | ESP  | CaCO <sub>3</sub> | OM   | Н    |
|------------|-------------|---------|----------------|---------|-------------------------|------|-------------------|------|------|
| Туре       | Site        | Sand    | Silt<br>(g/kg) | Clay    | (cmol <sub>c</sub> /kg) | (%)  | (g/kg)            |      | P    |
| Loamy sand | Basra       | 870     | 50             | 80      | 8.75                    | 1.1  | 1.26              | 0.8  | 7.11 |
| Loam       | Nevatim     | 413     | 362            | 225     | 17.68                   | 2.10 | 182.4             | 12.2 | 7.82 |
| Sandy clay | Hafetz Haim | 465     | 154            | 381     | 34.76                   | 1.63 | 96.2              | 11.0 | 7.46 |
| Clay-Y     | Yagur       | 145     | 342            | 513     | 57.43                   | 1.64 | 202.0             | 17.6 | 7.61 |
| Clay-E     | Eilon       | 137     | 213            | 650     | 64.90                   | 1.12 | 4.62              | 18.2 | 7.33 |

Table 1. Selected properties of the soils studied
CEC, Cation exchange capacity; ESP, exchangeable sodium percentage; OM, organic matter; pH from saturated paste extract

by 600 by 80 mm in which rainfall of a known constant drop size was generated through a set of hypodermic needles (~1000) arranged at a spacing of 20 by 20 mm. Average droplet diameter was  $2.97\pm0.05$  mm. A drop fall height of 2.2 m was used to obtain drops with an impact velocity of 5.64 m/s and a kinetic energy of 15.9 kJ/m³ (Epema and Riezebos 1983). Rain intensity was maintained at 36 mm/h using a peristaltic pump.

Air-dried soils, crushed to pass through a 4.0-mm sieve, were packed in trays 200 by 400 mm, 40-mm deep, over a 20-mm thick layer of coarse sand. The bulk density of the soils in the trays was maintained at 1.41 ( $\pm 0.02$ ), 1.32 ( $\pm 0.02$ ), 1.24 ( $\pm 0.01$ ), and 1.23 ( $\pm 0.01$ ) g/cm<sup>3</sup> for the loamy sand, loam, sandy clay, and 2 clay soils, respectively. These bulk densities were generally similar to the natural bulk densities in cultivated fields and were obtained by adding the same amount of soil, in 200-g portions, into the trays and smoothing the soil surface after each soil addition. The trays were saturated from below with tap water (electrical conductivity of 0.9 dS/m and sodium adsorption ratio of 2.0) in order to facilitate the immediate measurement of IR rates during the subsequent rain simulation. The trays were then placed under the rain simulator at a slope of 15% (enabling the collection of most of the detached materials in the runoff flow), and exposed to 60 mm of deionised water rain (electrical conductivity  $\sim 0.004 \, dS/m$ ).

During each simulated rainfall event, water infiltrating through the soils was collected, at 4-min intervals, in graduated cylinders placed underneath an outlet in the bottom of the tray, and water volume was recorded as a function of time. Runoff water was collected in buckets continuously throughout the event, and its volume at the end of the event was determined. Subsequently, runoff water in each bucket was thoroughly mixed, and while mixing continued, 3 subsamples of known volume (~250 mL) were taken in beakers and dried, and the total amount of soil removed by runoff during the entire event was calculated. Splash from the soil trays was not measured. Three trays, constituting 3 replicates, were used concurrently in the same rainfall storm for each treatment.

# Treatments for rainfall simulation

Two types of anionic PAMs (A110 and Cyanamer P-26, from Cytec Inc., North Andover, MA) were used in this study. The A110, designated as PAM(H), had a high MW ( $1.2 \times 10^7$  Da) and 15% hydrolysis. The Cyanamer P-26, designated as PAM(M), had a moderate MW ( $2 \times 10^5$  Da) and 10% hydrolysis.

Four treatments were studied: (*i*) control (no addition of PAM or of PG); (*ii*) PG comprising 85% CaSO<sub>4</sub>, particle size <2 mm (4 Mg/ha); (*iii*) dry PAM(H) (20 kg/ha) + PG (4 Mg/ha); and (*iv*) dry PAM(M) (20 kg/ha) + PG (4 Mg/ha). Dry PAM granules and PG grains were spread uniformly on the surface of the soil packed in the trays, after the saturated soil trays were placed in the rainfall simulator and immediately before rain application.

### Statistical analysis

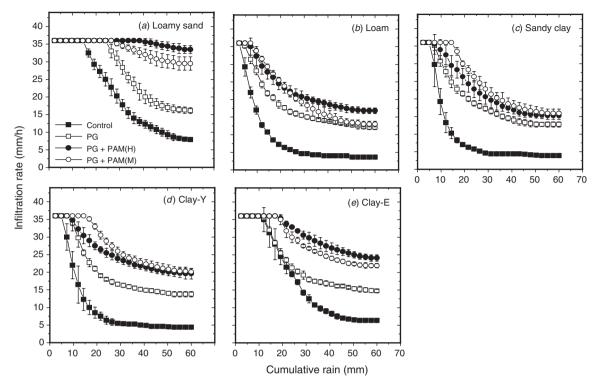
We studied 4 main treatments and 5 soil types in a fully factorial design, using 3 replicates per individual treatment. A multifactor analysis of variance (ANOVA) procedure was performed (SAS Institute 1995) to compare the effect of soil texture, treatments (PAM MW), and their interactions on infiltration, runoff, and erosion. Treatment mean comparisons were made by employing the Tukey-Kramer HSD test using a significance level of 0.05 (SAS Institute 1995).

#### Results and discussion

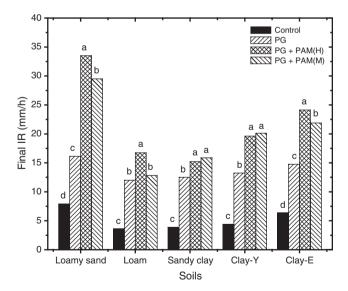
Effects of PG and PAM treatments on infiltration rate and runoff

Effects of cumulative rain on the measured IR of the 5 soils treated with the amendments are presented in Fig. 1. The amendments were effective in maintaining greater IR values compared with the control in all of the soils, and the degree of effectiveness of the amendments depended on soil type (Fig. 1). In general, the IR values for the PAM treatments were greater than those for the PG alone. The MW of the PAM influenced the depth of rain to ponding, i.e. the depth of rain needed to initiate runoff, but not in a consistent manner (Fig. 1). In the loamy sand, the depth of rain to ponding for the PAM(H) treatment was 41 mm, while that for the PAM(M) treatment was only 29 mm. In the other soils, depth of rain to ponding was <20 mm. Furthermore, unlike the loamy sand, the other soils had depths of rain to ponding for the PAM(M) treatment that were either similar to (loam and clay-E), or greater than (sandy clay and clay-Y), those for the PAM(H) treatment (Fig. 1).

In order to enable a quantitative comparison among the effects of the different treatments on soil susceptibility to seal formation, we examined the final IR and cumulative runoff for the 5 soils (Figs 2 and 3). A 2-way ANOVA indicated that each main treatment (soil type and amendment type), and their interaction, had a significant effect on both the final



**Fig. 1.** Measured infiltration rate curves of the 5 soils for the different treatments. Data points represent means of 3 replicates. Bars indicate 1 standard error. Control (no addition of polyacrylamide or phosphogypsum); PG, phosphogypsum (4 Mg/ha); PAM(H), polyacrylamide with high molecular weight (20 kg/ha); PAM(M), polyacrylamide with moderate molecular weight (20 kg/ha).



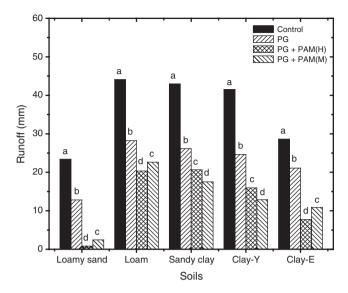
**Fig. 2.** Final infiltration rate (IR) as a function of the treatments for the 5 soils. Within a soil type, bars labelled with the same letter are not significantly different at P=0.05 level. Control (no addition of polyacrylamide or phosphogypsum); PG, phosphogypsum (4 Mg/ha); PAM(H), polyacrylamide with high molecular weight (20 kg/ha); PAM(M), polyacrylamide with moderate molecular weight (20 kg/ha).

IR and the cumulative runoff (Table 2); hence, separation among means of individual treatments within each soil type was performed.

In the control treatment, the soils with the smallest final IRs (3.6, 3.9, and 4.4 mm/h), and which generated the largest runoff amounts (44.0, 43.0, and 41.0 mm), were the loam, sandy clay, and clay-Y, respectively (Figs 2 and 3). As the clay percentage of the other 2 soils increased, or decreased, beyond those of these 3 soils, the final IR increased (6.4 and 7.9 mm/h) and the amount of runoff decreased significantly (23.4 and 28.6 mm) for the loamy sand and clay-E, respectively (Figs 2 and 3). The increase in final IR with the increase in clay percentage of clay-E resulted from the favourable impact that the increase in clay content had on improving aggregate stability (Levy and Mamedov 2002), while the increase in the final IR in the loamy sand (in which clay content was less than that in the loam, Table 1) was due to insufficient clay material for the formation of a well-developed seal (Ben-Hur *et al.* 1985).

Spreading PG, or PAM mixed with PG, on the soil surface increased the final IR by as much as 2–5 times, with values ranging from 12.0 to 33.5 mm/h when compared with untreated samples of the same soil type, and decreased the cumulative runoff, to levels of 1.0–28.2 mm (Figs 2 and 3). Furthermore, spreading the mixtures of dry PAM with PG resulted, in most cases, in significantly larger final IR values (12.8–33.5 mm/h) and smaller cumulative runoff values (1.0–22.6 mm) than those obtained when spreading PG alone (12.0–16.1 mm/h and 12.8–28.2 mm) (Figs 2 and 3, respectively).

Comparison of the effects of the 2 PAMs (combined with PG) on the final IR and cumulative runoff indicated that, in the loamy sand, loam, and clay-E, use of PAM(H) led to larger final IR and smaller cumulative runoff values than an application of



**Fig. 3.** Cumulative runoff as a function of the treatments for the 5 soils. Within a soil type, bars labelled with the same letter are not significantly different at P = 0.05 level. Control (no addition of polyacrylamide or phosphogypsum); PG, phosphogypsum (4 Mg/ha); PAM(H), polyacrylamide with high molecular weight (20 kg/ha); PAM(M), polyacrylamide with moderate molecular weight (20 kg/ha).

Table 2. Significance levels for treatment effects on the measured final infiltration rate (IR), cumulative runoff, and measured total soil loss \*\*\*P < 0.001

| Source          | d.f. | Sum of squares      | F ratio | Prob. > <i>F</i> |  |  |  |  |  |  |
|-----------------|------|---------------------|---------|------------------|--|--|--|--|--|--|
| Final IR (mm/h) |      |                     |         |                  |  |  |  |  |  |  |
| Soil (S)        | 4    | 870.13              | 191.08  | ***              |  |  |  |  |  |  |
| Treatments (T)  | 3    | 2537.81             | 743.06  | ***              |  |  |  |  |  |  |
| $S \times T$    | 12   | 340.25              | 24.91   | ***              |  |  |  |  |  |  |
| Model           | 19   | 3748.19             | 173.28  | ***              |  |  |  |  |  |  |
| Error           | 40   | 45.54               |         |                  |  |  |  |  |  |  |
| Total           | 59   | 3793.73             |         |                  |  |  |  |  |  |  |
|                 |      | Runoff (mm)         |         |                  |  |  |  |  |  |  |
| Soil            | 4    | 2899.58             | 251.06  | ***              |  |  |  |  |  |  |
| Treatments      | 3    | 5291.53             | 610.89  | ***              |  |  |  |  |  |  |
| $S\times T$     | 12   | 192.64              | 5.56    | ***              |  |  |  |  |  |  |
| Model           | 19   | 8383.75             | 152.82  | ***              |  |  |  |  |  |  |
| Error           | 40   | 115.49              |         |                  |  |  |  |  |  |  |
| Total           | 59   | 8499.24             |         |                  |  |  |  |  |  |  |
|                 |      | Soil loss $(g/m^2)$ |         |                  |  |  |  |  |  |  |
| Soil            | 4    | 879 520.4           | 118.89  | ***              |  |  |  |  |  |  |
| Treatments      | 3    | 1711519.8           | 308.47  | ***              |  |  |  |  |  |  |
| $S \times T$ 12 |      | 104 840.3           | 4.72    | ***              |  |  |  |  |  |  |
| Model 19        |      | 2 695 880.4         | 76.72   | ***              |  |  |  |  |  |  |
| Error           | 40   | 73 977.7            |         |                  |  |  |  |  |  |  |
| Total           | 59   | 2 769 858.1         |         |                  |  |  |  |  |  |  |

PAM(M) (Figs 2 and 3). Conversely, in the sandy clay and clay-Y, comparable final IR values were observed for the 2 PAM treatments, with cumulative runoff being less in the PAM(M) than in the PAM(H).

The favourable effects of using PG or granular PAM+PG on maintaining larger IR and smaller levels of runoff, when compared with a non-treated soil, are well documented (e.g. Levy and Sumner 1998; Sojka et al. 2007). However, the greater efficiency of the dry PAM and PG mixtures in maintaining larger final IR and smaller runoff values than those of the PG alone is not trivial because it has been observed that spreading dry PAM alone on the soil surface resulted in IR and runoff levels that were similar, or less, than those observed in an untreated soil (Yu et al. 2003). It was postulated that, in the absence of PG, addition of high MW PAM increased the viscosity of the percolating water, which resulted in decreased IR and increased runoff (Yu et al. 2003). The improved performance of PAM and PG mixtures over that of PG alone has also been noted in aggregate stability studies (Green et al. 2004; Mamedov et al. 2007). Our results suggest that in the presence of PG, the application of granular PAM benefits from 2 effects due to electrolyte released by PG dissolution: (i) stabilisation of soil aggregates by the reduction in clay dispersion and by the enhancement of the adsorption of polymer on soil particles at the soil surface, thereby reducing seal formation; and (ii) the presence of cations in the soil solution causing tighter coiling and greater contraction of the dissolved polymer chains, thereby reducing the viscosity of the PAM solution (Skupisan et al. 1998; Lu et al. 2002) and, consequently, lessening or eliminating the likelihood for reduced permeability in the soil surface pores (Malik and Letey 1992; Yu et al. 2003).

When comparing the effects of the 2 granular PAMs, mixed with PG, on infiltration, the following should be considered. PAM becomes effective in enhancing clay flocculation and aggregate stabilisation only when it dissolves and mixes with the soil solution. When a PAM granule at the soil surface comes into contact with raindrops, it initially absorbs water and turns into a gel that is relatively impermeable to water (Young et al. 2009). With continuing application of rainwater, the outer surface of the gel slowly dissolves and forms a very viscous PAM solution that becomes gradually less so as it moves away from the gel and mixes with the rain water. This process is also dependent on the initial size of the polymer granule, as smaller granules, such as those of the PAM(M), when compared with those of the PAM(H), generally will have higher specific surface areas and can dissolve and spread at a faster rate. However, in our study the granule sizes of the 2 polymers were comparable. Changes in the IR of the soil surface, as presented in Fig. 1, are determined, therefore, by (i) the surface area of the impermeable wet gel, (ii) the rate of decrease in the viscosity of the surface solution as it moves away from the impermeable gel or percolates into the soil, and (iii) the beneficial effect of the dissolved PAM on the stabilisation of the surface aggregates, and thus on preventing seal formation. Use of PAM(M) should have a beneficial effect on IR because of the lower viscosity of its percolating solution compared with that of the dissolved PAM(H) solution. Conversely, dissolved PAM(H) is expected to be more effective than PAM(M) in preventing seal formation due to its greater impact on clay flocculation and soil surface aggregate stabilisation (Malik and Letey 1991; Heller and Keren 2002).

Combined analysis of the depth of rain to ponding (Fig. 1), final IR (Fig. 2), and cumulative runoff data (Fig. 3) indicated that the effect of PAM MW was variable. For example, in the

loam, treatment with either PAM polymer resulted in a similar depth of rain to ponding, but the final IR was larger and cumulative runoff was smaller, in the PAM(H) treatment compared with that of PAM(M). Conversely, in the clay-Y, treatment with PAM(M) resulted in a greater depth of rain to ponding and similar final IR values for the 2 PAMs (Figs 1 and 2). These differences are ascribed to the opposing effects of MW on the IR. Higher MW leads to higher viscosity of the dissolved PAM solution (Volk and Friedrich 1980) and hence reduced IR (Malik and Letey 1992); conversely, the higher MW enhances clay flocculation and aggregate stability, thus preventing seal formation and maintaining high IR (Green et al. 2000, 2004). Thus, it is likely that the higher viscosity of PAM(H) becomes more of a factor in soils, such as the sandy clay and clay-Y, which have narrower soil surface pore systems (Mamedov et al. 2007), and which resulted in lower IRs than those observed in the case of PAM(M) (Fig. 1). In contrast, in the weakly structured loam, the greater stabilising ability of PAM (H) resulted in a more stable pore system and relatively higher IRs (Fig. 1).

In the case of the loamy sand, it is postulated that the greater effectiveness of PAM(H) compared with PAM(M) for all 3 parameters is associated with the low clay content of this soil (Table 1). In the loamy sand, the greater porosity and larger average distance between individual soil particles, hindered the ability of the PAM(M), with its shorter molecular chains compared with those of PAM(H), to stabilise adjacent particles (Tang *et al.* 2006).

## Effects of PG and PAM treatments on soil loss

Soil losses obtained from the 60-mm rainstorms for the 5 soils and the various PG and PAM treatments are presented in Fig. 4. A multifactor ANOVA test for the soil loss data showed, similar

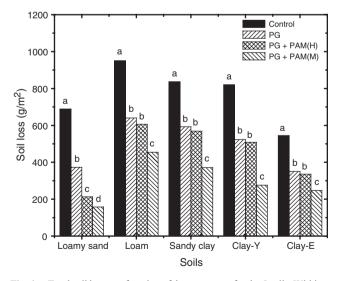


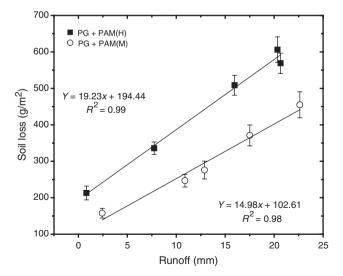
Fig. 4. Total soil loss as a function of the treatments for the 5 soils. Within a soil type, bars labelled with the same letter are not significantly different at P < 0.05 level. Control (no addition of polyacrylamide or phosphogypsum); PG, phosphogypsum (4 Mg/ha); PAM(H), polyacrylamide with high molecular weight (20 kg/ha); PAM(M), polyacrylamide with moderate molecular weight (20 kg/ha).

to the analysis for the final IR and cumulative runoff data, the existence of a significant interaction between soil type and the treatments being tested (Table 2); thus, comparisons among individual treatments within each soil type were performed (Fig. 4).

Soil erosion in the control treatment was greatest for the loam (950.8 g/m²) (Fig. 4). Similar to the pattern observed for cumulative runoff (Fig. 3), soil erosion in the loamy sand was less (688.5 g/m²) than that in the loam (Fig. 4). For the soils with clay contents greater than that of the loam, soil erosion tended, as reported in previous studies (e.g. Levy et al. 1994; Mamedov et al. 2001; Tang et al. 2006), to decrease gradually (<550.0 g/m²) with the increase in clay content (Fig. 4). However, for these same soils, the volume of runoff in the control treatments was almost unaffected by clay contents of up to 51% (clay-Y), but substantially decreased when clay content increased to 65% (clay-E) (Fig. 3). Similar data were presented by Tang et al. (2006).

Spreading PG on the soil surface was effective in significantly reducing soil loss (>1.4 times) compared with the control (Fig. 4). The effect of the PAM(H)+PG treatment on reducing soil erosion in all the soils, except for the loamy sand, was comparable to that of PG alone (Fig. 4). Similar observations were reported in previous studies that also investigated the effects of spreading granular PAM with gypsiferous material on soil losses (Peterson *et al.* 2002*b*; Yu *et al.* 2003; Tang *et al.* 2006). In the current study, the PAM(M) +PG treatment was significantly more effective than the PAM(H)+PG (1.3–1.8 times) in reducing soil loss (Fig. 4). Moreover, the difference between soil loss for PAM(M) and PAM(H) treatments increased with the increase in runoff volume (Fig. 5).

Severity of erosion depends upon the quantity of material supplied by detachment and the amount of runoff available to transport it. Interrill erosion may be detachment-limited (either



**Fig. 5.** Total soil loss as a function of cumulative runoff for the soils treated with 2 types of PAM. PG, phosphogypsum (4 Mg/ha); PAM(H), polyacrylamide with high molecular weight (20 kg/ha); PAM(M), polyacrylamide with moderate molecular weight (20 kg/ha). Bars indicate 1 standard error.

by rain splash or by runoff shear flow) or transport-limited (where more material is supplied than can be transported by overland flow). When the soil is exposed to raindrops, a seal is formed, IR decreases, and runoff increases. Seal formation may have 2 opposing effects on soil erosion: (i) seal development may increase the shear strength of the soil surface (Bradford et al. 1987) and thus reduce soil detachment and erosion (Moore and Singer 1990), and (ii) seal formation increases runoff volume and hence the capacity to transport the entrained material (Moore and Singer 1990). Taking both mechanisms into account could explain the apparent discrepancy whereby changes in the amount of runoff (Fig. 3) do not correspond exactly with those in soil loss levels (Fig. 4) for all the treatments studied, notably for the controls. Therefore, whereas runoff and IR were generally not affected by clay content in the range 22.5–51% clay, the observed decrease in soil loss over this range of clay contents could be associated with a corresponding increase in the shear strength of the soil surface (Mamedov et al. 2001). When clay content increased to 65%, soil loss decreased due to both an increase in the shear strength of the soil surface and the reduction in runoff amount (Figs 3 and 4). In addition, the highly significant linear relation between runoff and soil loss for the 2 PAM treatments (Fig. 5) suggests that, under our experimental conditions, soil losses from this treatment were controlled by the transport capacity of the runoff water.

It is postulated that the clear advantage of granular PAM(M) over granular PAM(H) with respect to the polymer's ability to control soil erosion (Figs 4 and 5) could be related to differences in the viscosity of the 2 PAM solutions that are formed at the soil surface during the rain event. As suggested previously, at the rain initiation, the dry PAM granules at the soil surface get wet and turn into an impermeable gel that, with continued application of rainwater, dissolves slowly and forms a viscous solution. The viscous PAM solution flows both vertically into the soil and laterally over the surface, downslope. The dissolved PAM(M), because of its lower MW, forms a less viscous solution than the dissolved PAM(H) (Volk and Friedrich 1980). Hence, because of its lower viscosity, the lateral flow component of the PAM(M) solution covers a greater soil surface area compared with the PAM(H) treatment. As a result, a greater portion of the surface aggregates is stabilised by the PAM(M) and is less susceptible to erosion. In addition, the more uniform presence of PAM(M) may increase the opportunity for flocculation of eroded particles already suspended in the runoff water and for subsequently greater rates of deposition of these entrained particles from the runoff water. Consequently, the use of PAM(M) has resulted in less soil erosion than when using PAM(H).

## **Summary and conclusions**

We have compared the effects of a surface application of 2 dry, anionic PAM polymers, varying in their MW ( $2 \times 10^5$  and  $2 \times 10^7$  Da), in combination with PG, to that of PG alone and to no amendment at all, on seal formation, runoff, and soil erosion in 5 smectitic soils varying in clay content. The 2 PAM polymers maintained final IR values that were greater, and runoff levels that were smaller, than those obtained in either

the control or PG alone treatments. However, their effects relative to each other were variable, probably because of opposing effects of PAM MW on seal permeability. A higher MW leads to higher viscosity of the dissolved PAM solution and thus reduced IR; conversely, it enhances clay flocculation and aggregate stability, thus reducing seal formation and maintaining larger IRs. PAM(M) was, however, more effective than PAM(H) in controlling soil erosion. The lower levels of soil erosion in the PAM(M) treatments were ascribed to its lower viscosity when in solution, which, in turn, enhanced the ability of this solution to more uniformly and efficiently cover and treat the soil surface aggregates. The treated soil surface resisted soil aggregate breakdown and detachment while enhancing deposition rates of eroded particles already present in the runoff water.

The observed advantage of PAM(M) over PAM(H) in controlling soil erosion was not in full agreement with previously published data where the effect of PAM MW was reported to depend on site-specific conditions. It is postulated that the disagreement may stem from differences in the methods of PAM application (i.e. dissolved PAM v. dry PAM granules). Further studies, including field trials, in which PAM is applied in the form of dry granules, are needed in order to validate our findings. Such studies may verify whether or not PAM MW is an important factor in polymer applications in a soil-specific management approach to controlling soil and water losses.

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